Observation of the $D_{sJ}(2463)$ and Confirmation of the $D_{sJ}^*(2317)$

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Using 13.5 fb^{-1} of e^+e^- annihilation data in the CLEO II detector at CESR, we have observed a new narrow state decaying to $D_s^{*+}\pi^o$, denoted the $D_{sJ}(2463)^+$. A possible interpretation holds that this is a $J^P = 1^+$ partner to the $D_{sJ}^*(2317)^+$ state recently discovered by the BaBar Collaboration which is consistent with $J^P = 0^+$. We have also confirmed the existence of the $D_{sJ}^*(2317)^+$ in its decay to $D_s^+\pi^o$. We have measured the masses of both states, accounting for the cross-feed background that the two states represent for each other, and have searched for other decay channels for both states. No narrow resonances are seen in $D_s^\pm\pi^\mp$ or $D_s^\pm\pi^\pm$ modes.

1 Introduction

Prior to this year, the spectrum of $c\overline{s}$ mesons was believed to be well-understood. The weakly-decaying ground state D_s^+ meson with mass 1969 MeV and $J^P = 0^-$ was discovered by CLEO in 1983. The excited 1^- state at 2112.4 MeV, the D_s^{*+} meson, is also narrow, decaying to the D_s^+ predominately via γ emission. It also has a 6% rate [1] for a strong transition via π^o emission [2], which violates isospin symmetry since all $c\overline{s}$ mesons are isospin singlets while the pion is an isospin triplet. These states both have zero orbital angular momentum between the two quarks.

Four states with $L = 1$ are expected, corresponding to a spin singlet and triplet, giving one state with $J^P = 0^+$, two with 1^+, and one with 2^+. Considering the charm quark to be heavy, it is more natural to think of these as two doublets with $j = 1/2$ and $3/2$, where j is the angular momentum sum of L with the spin of the strange quark. The $j = 3/2$ states are expected to be narrow because their dominant (OZI- and isospin-favored) decays to $D^{(*)}K$ will proceed via D-wave. Indeed, the experimental observations of the $D_{sJ}(2573)^+$ (with J^P consistent with 2^+) and the $J^P = 1^+$ $D_{s1}(2536)^+$ were made feasible by the fact that these states are narrow. Most, but not all, potential models expected the unobserved $j = 1/2$ states to have comparable masses, and to decay to same final states but with large widths, ~200-300 MeV, since these decays would proceed via S-wave.

BaBar has recently reported the discovery of a new narrow state, the $D_{sJ}^*(2317)^+$, in its decay to $D_s^+\pi^o$ [3], its width consistent with experimental resolution. The low mass, below DK threshold, implies that despite its isospin violation, the observed channel is the most likely hadronic decay available, thus explaining the narrow width. The BaBar data is also consistent with a 0^+ spin/parity interpretation.

Various interpretations of this state have appeared in the literature. To give some examples: Barnes, Close and Lipkin speculate that this could be "baryonia" or a DK molecule [4]. Van Beveran and Rupp suggest a quasi bound scalar that arises due to coupling to the nearby DK threshold [5]. Cahn and Jackson formulate an acknowledgely poor explanation using non-relativistic vector and scalar exchange forces [6].

Bardeen, Eichten and Hill (BEH) [7] use HQET plus chiral symmetry to predict "parity doubling," where two orthogonal linear combinations of mesons transform as $\mathrm{SU}(3)_L \times \mathrm{SU}(3)_R$ and split into $(0^-, 1^-)$, $(0^+, 1^+)$ doublets. Assuming that the $D_{sJ}^*(2317)$ is the 0^+ state expected in the quark model, their concrete prediction is that the mass splitting between the remaining 1^+ state and the 1^- should be the same as the $0^+ - 0^-$ splitting.

2 Confirmation of the $D_{sJ}^*(2317)$

D_s^+ candidates are looked for in the $\phi\pi^+$ decay mode. The selection criteria are described in detail in Ref. [8]. The $D_s^+\pi^o$ mass distribution is shown in Fig. 1 for mass combinations with momenta above 3.5 GeV/c. Two peaks are evident: one near a mass difference of 0.1 GeV, due to the decay of the D_s^{*+} into a $D_s^+\pi^o$, and another, larger structure near a mass difference of 0.35 GeV, that confirms the existence of the $D_{sJ}^*(2317)^+$. The measured width of this peak is $8.0^{+1.3}_{-1.2}$ MeV, somewhat wider than the detector resolution of 6.0±0.3 MeV. The curve shows our Monte Carlo simulation of the mass distribution, absolutely normalized, without the presence of any narrow states that decay into D_s^+ mesons. The CLEO Monte Carlo does an excellent job of reproducing the size and shape of our background π^o candidates.

The peak near 0.35 GeV is close to the mass reported by BaBar. Our mass determination will be discussed later. We observe 165±20 events in this peak.

3 Observation of the $D_{sJ}(2463)$

We also looked for decays of the $D_{sJ}^*(2317)^+$ and possible additional narrow states in other channels, notably $D_s^{*+}\pi^o$. We use the $D^{*+} \to \gamma D_s^+$ decay mode. Photon candidates were selected from neutral energy clusters with lateral profiles consistent with electromagnetic showers and absolute energies above 50 MeV. Fig. 2 shows the mass difference distributions for both the peak and sideband regions of the D_s^{*+} signal.

We observe a peak consisting of 55±10 events, with a width of 6±1.0 MeV (r.m.s.) compared with the detector resolution of 6.6±0.5 MeV. The mass difference value is also about 0.35 GeV. The near equality of this mass difference with the previous one leads to the worry that there could be cross-contamination between the two final states.

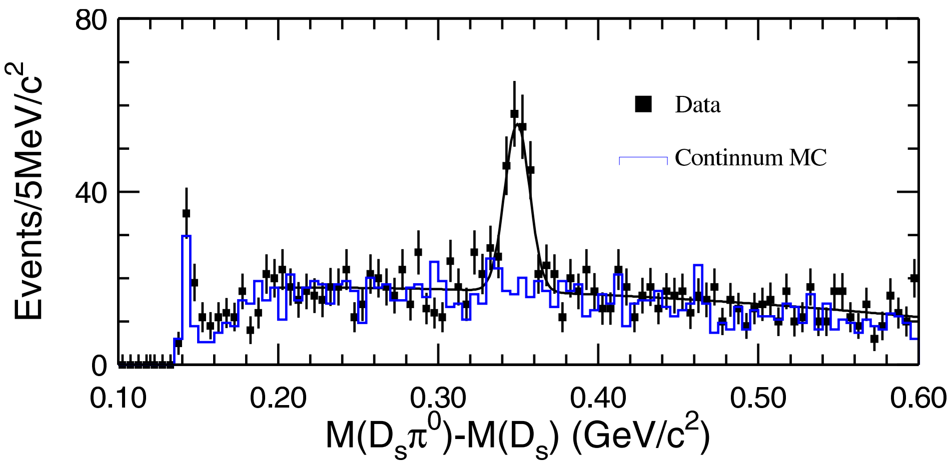

Figure 1: The $D_s^+\pi^o$ candidate mass distribution shown as the difference with respect to the D_s^+ mass. The curve shows our Monte Carlo simulation of the spectrum, absolutely normalized, without narrow states decaying into D_s^+.

4 Analysis of Cross Contamination

Many studies were performed to see if these two states could arise from reflections of other known narrow states. These possibilities were excluded.

It is possible, however, for a higher mass state decaying $D_s^{*+}\pi^o$ to be reconstructed as a lower mass state simply by ignoring the photon from the D_s^{*+} decay. In fact, taking the signal $D_s^{*+}\pi^o$ events and ignoring the photon from the D_s^{*+} decay causes a peak in the $D_s^+\pi^o$ spectrum at very nearly the same mass difference, but with a width of 14.9 MeV, considerably larger than our resolution. The efficiency of this process is rather high: (84±4±10)%.

It is also possible for the lower mass state to pick up a random photon, fake a D_s^{*+}, and thus be a candidate for the upper mass state. This is a much smaller probability, (9.0±0.7±1.5)% and can be estimated from the D_s^{*+} sidebands. The number of actual signal events can be estimated from these probabilities and the measured numbers of events in the peaks. Accounting for the background in this way, the peak in the $D_s^{*+}\pi^o$ sample corresponds to 41±12 signal events. The probability that this excess is due to a background fluctuation is in excess of 5σ. Thus CLEO has made the first observation of a new state near 2460 MeV. (Although the BaBar data also showed an excess of events in this mass region, the conclusion reached in Ref. [3] was that further study was needed to resolve whether the peak received contributions from a new state or was entirely due to a reflection of the $D_{sJ}^*(2317)$.)

5 Mass Determinations

Because of the contamination of the lower mass state by the higher mass one, fitting the $D_s\pi^o - D_s$ mass difference distribution to a single Gaussian could result in a biased mass determination. Taking advantage of the the excellent mass resolution of the CLEO CsI calorimeter we fit the

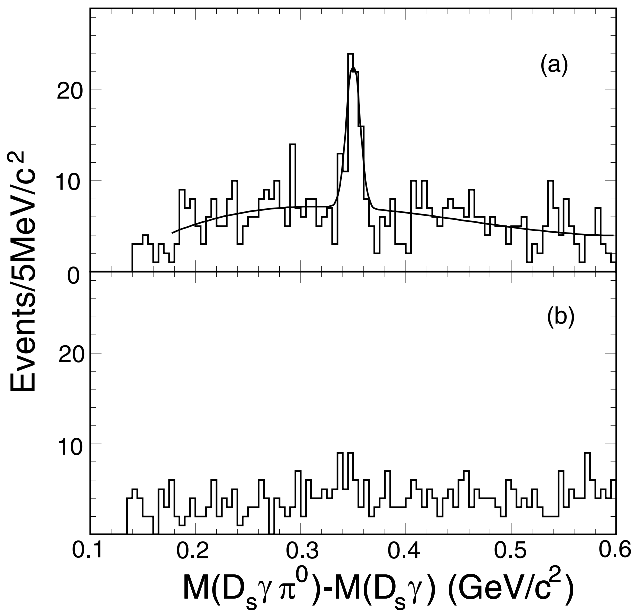

Figure 2: The $D_s^{*+}\pi^o$ candidate mass distribution shown as the difference with respect to the D_s^{*+} mass. (a) D_s^{*+} signal region; (b) D_s^{*+} sideband region.

$D_s^+\pi^o$ mass difference peak to two Gaussians whose means and widths are allowed to float. The fit determines one signal to be at a mean mass difference of 350.0±1.2 MeV with a width of 5.9±1.2 MeV and another wider Gaussian at 344.9±6.1 MeV with a width of 16.5±6.3 MeV, characteristic of the feed-down background. We use this fit for our determination of the mass difference, to which we assign a ±1.0 MeV systematic error.

Since the feedup from the first state to the second state is relatively small, ∼20% of the signal of the higher mass state, we determine its mass by subtracting the D_s^* sidebands and performing a fit. The subtracted spectrum and the fit are shown in Fig. 3. The resulting mass difference is 351.2±1.7 MeV, to which we also assign a systematic error of ±1.0 MeV.

We note that a $D_s^+\pi^o$ system with $L = 0$ is a 0^+ state, and a $D_s^{*+}\pi^o$ system with $L = 0$ is a 1^+ state. If the $D_{sJ}(2463)$ were a 0^+ state it would be above threshold for decay into DK. There is no evidence for this state in that decay mode and if that decay occurred the state would be wide.

6 Upper Limits On Other Decay Modes

6.1 Neutral and Doubly Charged Modes

In Fig. 4 we show the $D_s^{\pm}\pi^{\mp}$ and $D_s^{\pm}\pi^{\pm}$ mass difference distributions. No signals are visible and the production ratio times decay rate of any objects similar to the $D_{sJ}^*(2317)$ are lower by more than a factor of ten compared to the $D_s^{*+}\pi^o$ mode. This argues against a molecular interpretation.

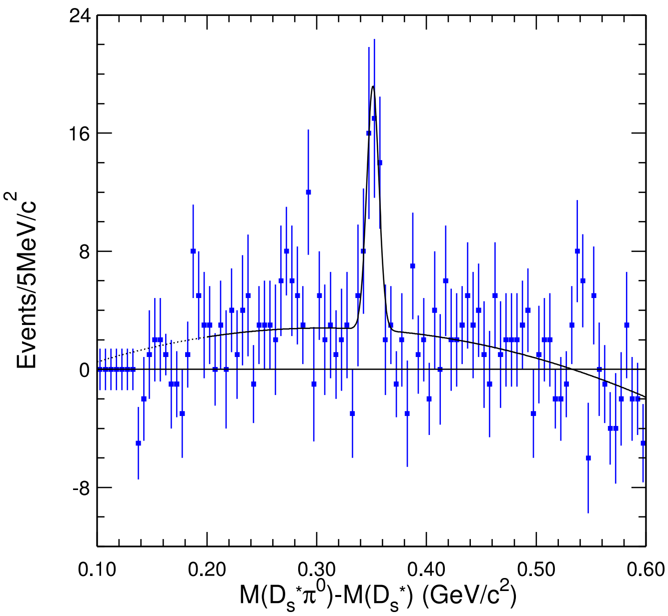

Figure 3: The sideband subtracted $D_s^{*+}\pi^o$ candidate mass difference distribution. The curve resents a fit to a signal Gaussian whose mean and width are allowed to float and a second order background polynomial.

6.2 Other Decay Modes of the $D_{sJ}^*(2317)$

Upper limits on other decay modes relative to the $D_s^+\pi^o$ mode are given in Table 1.

6.3 Other Decay Modes of the $D_{sJ}(2463)$

Limits obtained on other decays, relative to $D_s^*\pi^0$, are summarized in Table 2.

This electromagnetic transition to $D_{sJ}^*(2317)^+\gamma$ [9] presents a particularly difficult situation as the final state particles are again a D_s^+ a π^o and a γ with momenta similar to that in the main $D_s^{*+}\pi^o$ mode. To reduce backgrounds from $D_{sJ}(2463)^+ \to D_s^{*+}\gamma$, we required that

Final State	Yield	Efficiency	Ratio (90% C.L.)	Prediction
$D_s^+\pi^0$	135 ± 23	$(9.7 \pm 0.6)\,\%$	—	
$D_s^+\gamma$	-19 ± 13	$(18.1 \pm 0.1)\,\%$	< 0.052	0
$D_s^{*+}\gamma$	-6.5 ± 5.2	$(7.0 \pm 0.5)\,\%$	< 0.059	0.08
$D_s^+\pi^+\pi^-$	2.0 ± 2.3	$(19.8 \pm 0.8)\,\%$	< 0.019	0
$D_s^{*+}\pi^0$	-1.7 ± 3.9	$(3.6 \pm 0.3)\,\%$	< 0.11	0

Table 1: The 90% C.L. upper limits on the ratio of branching fractions for $D_{sJ}^*(2317)$ to the the channels shown relative to the $D_s^+\pi^0$ state. Also shown are the theoretical expectations from Ref. [7], under the assumption that the $D_{sJ}^*(2317)$ is the lowest-lying 0^+ $c\overline{s}$ meson.

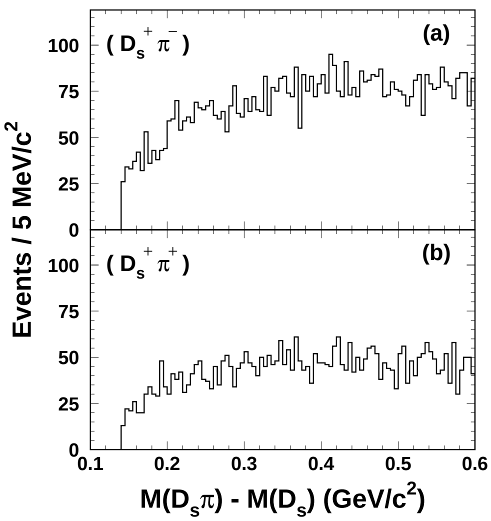

Figure 4: Mass difference distributions for $D_s^{\pm}\pi^{\mp}$ (top) and $D_s^{\pm}\pi^{\pm}$ (bottom) candidate samples.

Final State	Yield	Efficiency	Ratio (90% C.L.)	Prediction
$D_s^{*+}\pi^0$	41 ± 12	$(6.0 \pm 0.2)\,\%$	—	
$D_s^+\gamma$	40 ± 17	$(19.8 \pm 0.4)\,\%$	< 0.49	0.24
$D_s^{*+}\gamma$	-5.1 ± 7.7	$(9.1 \pm 0.3)\,\%$	< 0.16	0.22
$D_s^+\pi^+\pi^-$	2.5 ± 5.4	$(19.5 \pm 1.5)\,\%$	< 0.08	0.20
$D_{sJ}^*(2317)^+\gamma$	3.6 ± 3.0	$(2.0 \pm 0.1)\,\%$	< 0.58	0.13

Table 2: The 90% C.L. upper limits on the ratio of branching fractions for $D_{sJ}(2463)$ to the the channels shown relative to the $D_s^{*+}\pi^0$ state. Also shown are the theoretical expectations from Ref. [7], under the assumption that the $D_{sJ}(2463)$ is the lowest-lying 1^+ $c\overline{s}$ meson.

the $D_s\pi^0$ system be consistent with the decay of the $D_{sJ}^*(2317)$, namely that $|\Delta M(D_s\pi^0) - 350.0\,\mathrm{MeV/c^2}| < 13.4\,\mathrm{MeV/c^2}$ ($\sim 2\sigma$ based on Monte Carlo simulations). We also required that the $D_s\gamma$ system be inconsistent with D_s^* decay at the 1σ level (the corresponding $\Delta M(D_s\gamma)$ must deviate from the expected value for this decay by more than 4.4 MeV/c^2), and that the momentum of the π^0 be inconsistent with the $D_{sJ}(2463) \to D_s^*\pi^0$ transition, also at the 1σ level. Using these cuts, we see no evidence for a signal in this mode.

We note that our upper limit for $D_{sJ}(2463) \to D_s^+\pi^+\pi^-$ is considerably smaller than the BEH prediction. For this prediction they calculate both the isospin-violating $D_s^{*+}\pi^o$ rate and the decay into D_s^{*+} and a virtual σ meson that materializes as a $\pi^+\pi^-$ pair. Although this is a difficult calculation, we should not be far from seeing this decay.

7 Conclusions

CLEO confirms the $c\bar{s}$ state near 2317 MeV discovered by BaBar, and measures a mass difference with respect to the D_s^+ of 350.0±1.2±1.0 MeV. This state is likely to have $J^P = 0^+$.

CLEO has made the first observation of a new state near 2463 MeV and has measured $M(D_{sJ}(2463)) - M(D_s^+) = 351.2 \pm 1.7 \pm 1.0$ MeV. This is likely to be a 1^+ state. The mass splittings are consistent with being equal, as predicted by BEH; the difference $[((1^+ - 1^-) - (0^+ - 0^-)]$ being 1.2±2.1 MeV. The two states are narrow and we limit the total decay widths of both of them to be $\Gamma < 7$ MeV.

We also do not see evidence for any narrow states in $D_s^{\pm}\pi^{\mp}$ or $D_s^{\pm}\pi^{\pm}$, which argues against a molecular interpretation.

Theoretical applications of QCD, including exploitation of lattice QCD, sum rules, and heavy quark and chiral symmetries, are necessary to extract information on fundamental parameters in the quark sector. By coupling HQET with chiral symmetry, the BEH model yielded predictions about masses, widths and decay modes that were in conflict with conventional thinking based on potential models. The experimental results reported here provide powerful support for the BEH approach.

Acknowledgments

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[9] The calculation of cross feed backgrounds did not account for the possibility of $D_{sJ}(2463) \rightarrow D_{sJ}^*(2317)\gamma$ decays. However, based on our direct search for this decay, the impact of ignoring this channel is insignificant.